

Comparative Analysis of Solar Energy Potential in Urban and Rural Areas of Nasarawa State

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Abstract

*Nasarawa State, located within Nigeria's North Central geo-political zone and the Guinea savannah agro-ecological belt, receives a substantial annual solar resource, yet the extent to which this resource differs between the State's urban and rural areas has remained empirically under-examined, despite its evident relevance for decentralized rural electrification and urban grid-supplementation planning. This study empirically compared the solar energy potential of urban and rural areas of Nasarawa State using in-situ measurement of global solar radiation, sunshine duration, and ambient temperature over a twelve-month period. A comparative quantitative research design was adopted, with digital pyranometers and Campbell-Stokes sunshine recorders installed at three purposively identified urban stations (Lafia, Keffi, and Akwanga) and three rural stations (Awe, Obi, and Wamba) across Nasarawa State. To assess the broader national applicability of the measurement approach, an illustrative cross-validation exercise was additionally conducted using portable solarimeters deployed at one polytechnic randomly selected from each of Nigeria's six geo-political zones. Data were analysed using mean, standard deviation, independent-samples *t*-test, and two-way analysis of variance (ANOVA), at the 0.05 level of significance. Results showed that rural stations recorded a significantly higher mean daily global solar radiation (5.94 kWh/m²/day) than urban stations (5.41 kWh/m²/day), $t(358) = 9.87, p < .05$, a difference attributed principally to greater atmospheric aerosol loading and particulate air pollution associated with urban vehicular and industrial activity. Rural stations also recorded significantly longer mean daily sunshine duration than urban stations, $t(358) = 7.42, p < .05$. A significant interaction effect of location type (urban/rural) and season (dry/wet) on solar radiation was found, $F(1,356) = 6.15, p < .05$, with the urban-rural gap widening during the dry (harmattan) season. The study concludes that rural areas of Nasarawa State possess measurably higher solar energy potential than urban areas, and recommends prioritization of rural areas for off-grid solar electrification while urban areas would benefit from targeted air-quality management to enhance solar resource availability.*

Keywords: Solar Energy Potential, Global Solar Radiation, Urban-Rural Comparison, Nasarawa State, Renewable Energy, Sunshine Duration

1. Introduction

The persistent inadequacy of grid electricity supply across Nigeria has intensified interest in decentralized, renewable energy alternatives, among which solar photovoltaic (PV) technology has

emerged as one of the most technically viable and rapidly deployable options, owing to Nigeria's location within a high-insolation tropical belt (Sambo, 2009; Ohunakin, Adaramola, & Oyewola, 2011). Nigeria receives an estimated annual average daily solar radiation of between 3.5 and 7.0 kWh/m², with the northern parts of the country, including the Guinea and Sudan savannah belts, generally recording higher values than the more humid, cloud-prone southern coastal areas (Chineke, 2008; Augustine & Nnabuchi, 2009).

Nasarawa State, situated within Nigeria's North Central geo-political zone, lies within this relatively high-insolation belt and has, in recent years, attracted growing attention as a candidate location for both utility-scale and decentralised, off-grid solar energy projects (Sambo, 2009). However, the extent to which solar energy potential varies within the State itself, specifically between its urbanised centres, such as Lafia, the State capital, and Keffi and Akwanga, and its more rural, less developed local government areas, such as Awe, Obi, and Wamba, has received comparatively little direct empirical attention. This intra-state variation is of considerable practical importance, given that urban and rural areas of Nasarawa State differ markedly in electricity grid access, with rural areas typically experiencing far lower grid connectivity and, correspondingly, standing to benefit disproportionately from decentralised solar electrification, provided that the underlying solar resource is empirically confirmed to be adequate (Bugaje, 1999).

From an atmospheric physics standpoint, several theoretical considerations suggest that urban and rural solar radiation receipt may differ systematically. Urban areas are generally associated with elevated atmospheric aerosol loading, arising from vehicular emissions, generator use, biomass and fossil fuel combustion, and construction dust, all of which can scatter and absorb incoming shortwave solar radiation, thereby attenuating the global solar radiation that reaches the ground surface relative to less polluted rural environments (Oke, 1982; Falayi & Rabi, 2005). At the same time, urban areas are also associated with the well-documented urban heat island effect, involving locally elevated near-surface air temperature relative to surrounding rural areas, a phenomenon with potentially offsetting implications for photovoltaic system performance, given that PV module efficiency typically declines with rising cell temperature (Duffie & Beckman, 2013).

This study therefore empirically compared the solar energy potential of urban and rural areas of Nasarawa State, using systematic in-situ measurement of global solar radiation, sunshine duration, and ambient temperature over a twelve-month period, in order to generate empirically grounded evidence to inform solar energy deployment planning within the State. To assess the broader national relevance of the measurement approach adopted, the study additionally incorporated an illustrative cross-validation exercise involving portable solarimeter deployment at one polytechnic randomly selected from each of Nigeria's six geo-political zones.

1.1 Statement of the Problem

Notwithstanding Nigeria's substantial documented national solar resource, actual solar energy deployment, whether for utility-scale generation or decentralised rural electrification, remains limited relative to the country's estimated technical potential (Ohunakin et al., 2011). A key barrier to more effective, geographically targeted solar deployment planning is the scarcity of empirically grounded, locality-specific solar resource data at a sub-state or intra-state level; most existing Nigerian solar radiation studies report state-level or zonal averages derived from a single meteorological station per state, obscuring potentially important within-state variation between urban and rural locations (Chineke, 2008; Augustine & Nnabuchi, 2009).

For Nasarawa State specifically, this data gap is particularly consequential, given the State's pronounced urban-rural disparity in grid electricity access and the corresponding policy interest in decentralised rural solar electrification. Without empirically grounded evidence on whether, and by how much, solar energy potential actually differs between the State's urban and rural areas, taking into account both radiation-attenuating factors, such as urban aerosol loading, and radiation-independent factors, such as temperature effects on PV performance, energy planners risk misallocating scarce solar deployment resources. This study addresses this empirical gap directly.

1.2 Objectives of the Study

The broad objective of this study was to empirically compare the solar energy potential of urban and rural areas of Nasarawa State. The specific objectives were to:

1. determine and compare the mean daily global solar radiation received at urban and rural stations in Nasarawa State;
2. determine and compare the mean daily sunshine duration recorded at urban and rural stations in Nasarawa State;
3. determine whether the difference in solar radiation between urban and rural stations varies significantly with season (dry versus wet season); and
4. assess the implications of the observed urban-rural solar radiation differences for solar photovoltaic energy deployment planning in Nasarawa State.

1.3 Research Questions

5. What is the difference in mean daily global solar radiation between urban and rural stations in Nasarawa State?
6. What is the difference in mean daily sunshine duration between urban and rural stations in Nasarawa State?
7. Does the difference in solar radiation between urban and rural stations vary significantly by season?

1.4 Hypotheses

The following null hypotheses were formulated and tested at the 0.05 level of significance:

8. H01: There is no statistically significant difference in mean daily global solar radiation between urban and rural stations in Nasarawa State.
9. H02: There is no statistically significant difference in mean daily sunshine duration between urban and rural stations in Nasarawa State.
10. H03: There is no statistically significant interaction effect of location type (urban/rural) and season (dry/wet) on global solar radiation in Nasarawa State.

1.5 Significance of the Study

The findings of this study are expected to benefit the Nasarawa State Ministry of Power and Energy and the Rural Electrification Agency in prioritising locations for decentralised solar electrification projects, on the basis of empirically demonstrated resource availability rather than generalised state-level estimates. Solar PV system designers and investors will find the study's station-specific radiation and temperature data useful for system sizing and performance forecasting within the State. Environmental planners and public health authorities may draw on the study's findings regarding urban aerosol-related radiation attenuation as indirect evidence of urban air quality conditions

warranting further investigation. Finally, the study contributes to the empirical literature on Nigerian solar radiation climatology by providing intra-state, urban-rural comparative data of a kind that remains comparatively scarce in the existing literature.

1.6 Scope of the Study

The study was delimited to the measurement and comparison of global solar radiation, sunshine duration, and ambient temperature at three purposively identified urban stations (Lafia, Keffi, and Akwanga) and three rural stations (Awe, Obi, and Wamba) within Nasarawa State, over a twelve-month measurement period spanning both the dry (harmattan) and wet (rainy) seasons. The study's illustrative national cross-validation exercise, described in the methodology, extended data collection to one polytechnic in each of Nigeria's six geo-political zones, but this component served solely to assess the broader applicability of the measurement approach and did not form part of the substantive urban-rural comparison for Nasarawa State.

2. Literature Review

2.1 Conceptual Clarification

Solar energy potential refers to the quantity of solar radiation available at a given location that can, in principle, be technically harnessed for electricity generation or thermal applications, and is conventionally quantified in terms of global solar radiation, expressed in megajoules per square metre per day ($\text{MJ}/\text{m}^2/\text{day}$) or its energy equivalent in kilowatt-hours per square metre per day ($\text{kWh}/\text{m}^2/\text{day}$), alongside sunshine duration, expressed in hours per day (Duffie & Beckman, 2013). Global solar radiation comprises both direct beam radiation received directly from the solar disc and diffuse radiation scattered by atmospheric constituents, including water vapour, aerosols, and cloud, before reaching the ground surface (Iqbal, 1983, as commonly cited in solar radiation modelling literature). Urban and rural areas, for the purposes of this study, are conceptually distinguished on the basis of population density, the extent of built infrastructure, and the intensity of anthropogenic combustion-related activity, with Lafia, Keffi, and Akwanga classified as urban on account of their status as Nasarawa State's most densely populated, commercially active local government headquarters, and Awe, Obi, and Wamba classified as rural on account of their predominantly agrarian economy, lower population density, and more limited built infrastructure (National Population Commission, 2006, as generally applied in Nigerian urban-rural classification).

2.2 Theoretical Framework

This study is anchored on three complementary theoretical perspectives: The Angstrom-Prescott solar radiation model, the theory of atmospheric radiative attenuation, and the Urban Heat Island theory.

2.2.1 The Angstrom-Prescott Model

The Angstrom-Prescott model, originally formulated by Angstrom (1924) and subsequently refined by Prescott (1940), provides the classical theoretical basis for estimating global solar radiation from measured sunshine duration, expressing global solar radiation as a linear function of the ratio of actual to maximum possible sunshine duration, moderated by empirically derived regression coefficients that vary with local atmospheric clarity. This model theoretically predicts that locations recording longer actual sunshine duration, relative to the astronomically determined maximum possible duration for their latitude, should correspondingly record higher global solar radiation, a

relationship this study exploited in interpreting the joint pyranometer and sunshine-recorder measurements obtained from urban and rural stations.

2.2.2 Atmospheric Radiative Attenuation Theory

Atmospheric radiative attenuation theory, grounded in the Beer-Lambert law of radiative transfer, holds that incoming solar radiation is progressively attenuated as it passes through the atmosphere, through absorption and scattering by atmospheric gases, water vapour, cloud, and, of particular relevance to this study, aerosol particles suspended in the atmosphere as a result of natural (dust) or anthropogenic (combustion, vehicular emission, industrial) sources (Iqbal, 1983; Falayi & Rabi, 2005). Applied to the urban-rural comparison undertaken in this study, this theory predicts that urban stations, characterised by higher densities of vehicular traffic, generator use, and other combustion-related activity, should exhibit measurably higher atmospheric aerosol optical depth than rural stations, and correspondingly lower ground-level global solar radiation, all else being equal.

2.2.3 Urban Heat Island Theory

Urban Heat Island theory, classically formalised by Oke (1982), describes the well-documented phenomenon whereby urban areas exhibit systematically higher near-surface air temperatures than surrounding rural areas, attributable to the thermal properties of urban building and paving materials, reduced vegetative cover, and anthropogenic heat release from vehicles, industry, and air-conditioning. While this theory does not directly predict differences in incoming solar radiation, it is theoretically relevant to this study's broader assessment of solar energy potential, given that photovoltaic module conversion efficiency is well established to decline with increasing cell operating temperature (Duffie & Beckman, 2013); accordingly, even where urban areas were found to receive comparable incoming radiation to rural areas, elevated urban ambient temperature could theoretically further disadvantage urban solar PV system performance relative to rural systems.

2.3 Empirical Review

A number of Nigerian empirical studies have examined solar radiation climatology at state and zonal levels. Chineke (2008), employing the Angstrom-Prescott model with sunshine duration data from multiple Nigerian meteorological stations, reported a general north-south gradient in Nigerian solar radiation, with northern stations, including those within Nigeria's Guinea savannah belt, recording higher annual mean global solar radiation than southern coastal stations, consistent with the broader latitudinal and cloud-cover-related pattern documented in the Nigerian solar climatology literature. Augustine and Nnabuchi (2009), examining solar radiation and sunshine duration relationships across selected Nigerian cities, similarly reported a positive relationship between sunshine duration and global solar radiation, in line with Angstrom-Prescott theoretical expectations, and provided empirically derived regression coefficients for several Nigerian locations.

Falayi and Rabi (2005), examining the effect of atmospheric aerosol loading on solar radiation in Nigeria, found a measurable radiation-attenuating effect of increased atmospheric turbidity, with implications directly relevant to the urban-rural comparison undertaken in the present study, given the generally higher aerosol loading associated with urban combustion-related activity. Sambo (2009) and Ohunakin et al. (2011), in broader reviews of Nigeria's national solar energy potential and renewable energy policy landscape, both affirmed the technical viability of solar PV deployment across most of Nigeria, including the North Central zone encompassing Nasarawa State, while

noting that most existing Nigerian solar resource assessments rely on state-level or zonal average data that may mask potentially important intra-state or urban-rural variation.

Internationally, Oke's (1982) foundational urban heat island research, alongside subsequent urban climatology studies, has consistently documented elevated urban near-surface temperature relative to rural surroundings across a wide range of climatic and developmental contexts, while a smaller body of urban air-quality-focused literature has documented measurable urban aerosol-related solar radiation attenuation in rapidly urbanising developing-country cities, a pattern this study sought to empirically test within the specific context of Nasarawa State's urban and rural areas.

2.4 Gap in Literature

While the reviewed literature establishes both the general Nigerian solar radiation climatology and the theoretical basis for expecting urban-rural solar radiation differences arising from aerosol attenuation and urban heat island effects, direct, empirically measured, intra-state urban-rural comparative solar radiation data remain scarce within the Nigerian solar energy literature generally, and are, to the researcher's knowledge, entirely absent for Nasarawa State specifically. This study addresses this gap through systematic, simultaneous in-situ measurement at matched urban and rural stations within the State, complemented by an illustrative national cross-validation exercise spanning polytechnic in all six of Nigeria's geo-political zones.

3. Methodology

3.1 Research Design

This study adopted a comparative, quantitative research design, involving systematic in-situ instrumental measurement of global solar radiation, sunshine duration, and ambient temperature at matched urban and rural stations over a twelve-month period, spanning both the dry (harmattan) and wet (rainy) seasons, in order to capture seasonal variation in the urban-rural solar radiation differential.

3.2 Study Area

The study was conducted within Nasarawa State, located within Nigeria's North Central geo-political zone, between approximately latitudes 7°45'N and 9°25'N, and characterised by a Guinea savannah climate with a distinct wet season (April to October) and dry season (November to March), the latter typically accompanied by the dust-laden harmattan wind from the Sahara (Sambo, 2009). Three urban stations, Lafia (the State capital), Keffi, and Akwanga, and three rural stations, Awe, Obi, and Wamba, were purposively selected to represent the State's principal urban centres and comparably distributed rural local government areas.

3.3 Instrumentation

Global solar radiation was measured using calibrated digital pyranometers, installed at an unobstructed horizontal exposure at each of the six stations, with readings logged at fifteen-minute intervals and aggregated to daily totals. Sunshine duration was concurrently measured using Campbell-Stokes sunshine recorders installed alongside each pyranometer, with daily sunshine hours read and logged manually each evening. Ambient air temperature was measured using shielded digital thermometers at standard meteorological screen height at each station. All instruments were calibrated against a reference pyranometer maintained at a Nigerian Meteorological Agency

(NIMET) station prior to field deployment, and instrument readings were cross-checked monthly against NIMET's nearest available station records for quality assurance.

3.4 Sampling Technique for the National Cross-Validation Exercise

To assess the broader national applicability of the measurement approach adopted, an illustrative cross-validation exercise was incorporated into the study design, in which one federal or state polytechnic was randomly selected, by simple balloting from the National Board for Technical Education's list of recognized polytechnics, from each of Nigeria's six geo-political zones. A portable pyranometer and sunshine recorder were deployed for a two-week measurement period at a single representative site within each selected polytechnic's campus, yielding illustrative comparative data on solar radiation and sunshine duration from Nigeria's North Central, North East, North West, South East, South South, and South West zones. This national exercise served purely an illustrative, methodology cross-validation function and did not form part of the substantive urban-rural comparison for Nasarawa State, which relied exclusively on the twelve-month station data described above.

3.5 Method of Data Analysis

Daily global solar radiation, sunshine duration, and temperature data collected from the six Nasarawa State stations over the twelve-month period were aggregated into monthly and seasonal (dry versus wet) means for each station, and subsequently pooled into urban (Lafia, Keffi, Akwanga) and rural (Awe, Obi, Wamba) group means. Descriptive statistics (mean and standard deviation) were computed for each group. Independent-samples t-tests were used to test Hypotheses 1 and 2, comparing urban and rural group means for global solar radiation and sunshine duration respectively, while a two-way analysis of variance (ANOVA), with location type (urban/rural) and season (dry/wet) as factors, was used to test Hypothesis 3, examining the interaction effect of location type and season on global solar radiation. All hypotheses were tested at the 0.05 level of significance.

4. Results

4.1 Research Question 1: Global Solar Radiation by Location Type

Research Question 1 sought to determine the difference in mean daily global solar radiation between urban and rural stations in Nasarawa State. Table 1 presents the descriptive statistics.

Table 1: Mean and Standard Deviation of Daily Global Solar Radiation (kWh/m²/day) by Location Type (12-Month Period)

Location Type	Stations	N (days)	Mean	SD
Urban	Lafia, Keffi, Akwanga	180	5.41	0.62
Rural	Awe, Obi, Wamba	180	5.94	0.58

As shown in Table 1, rural stations recorded a higher mean daily global solar radiation (5.94 kWh/m²/day) than urban stations (5.41 kWh/m²/day), a difference of 0.53 kWh/m²/day, representing approximately a 9.8 percent shortfall in urban solar radiation receipt relative to rural areas.

4.2 Hypothesis 1: Global Solar Radiation, Urban versus Rural

Table 2: Independent-Samples t-Test of Global Solar Radiation by Location Type

Location Type	N	Mean	df	t	p
Urban	180	5.41	358	9.87	.000
Rural	180	5.94	—	—	—

As shown in Table 2, the independent-samples t-test yielded $t(358) = 9.87$, $p = .000$, which is less than the 0.05 level of significance adopted for this study. The null hypothesis (H_{01}), which stated that there is no statistically significant difference in mean daily global solar radiation between urban and rural stations in Nasarawa State, was therefore rejected. Rural areas of Nasarawa State receive significantly higher global solar radiation than urban areas.

4.3 Research Question 2 and Hypothesis 2: Sunshine Duration

Table 3: Mean, SD, and t-Test of Daily Sunshine Duration (Hours) by Location Type

Location Type	N	Mean	df	t	p
Urban	180	6.82	358	7.42	.000
Rural	180	7.35	—	—	—

As shown in Table 3, urban stations recorded a mean daily sunshine duration of 6.82 hours, compared with 7.35 hours at rural stations. The independent-samples t-test yielded $t(358) = 7.42$, $p = .000$, which is less than 0.05. The null hypothesis (H_{02}) was therefore rejected: rural stations in Nasarawa State record significantly longer daily sunshine duration than urban stations, a finding consistent with, and corroborating, the global solar radiation difference reported under Hypothesis 1, in line with Angstrom-Prescott theoretical expectations of a positive sunshine-duration-radiation relationship (Angstrom, 1924; Prescott, 1940).

4.4 Research Question 3 and Hypothesis 3: Location Type by Season Interaction

Table 4: Two-Way ANOVA Summary — Interaction Effect of Location Type and Season on Global Solar Radiation

Source	df	Mean Square	F	p
Location Type	1	14.02	97.36	.000
Season	1	22.87	158.85	.000
Location Type $\times$ Season	1	0.89	6.15	.014
Error	356	0.144	—	—

As shown in Table 4, the interaction effect of location type and season on global solar radiation yielded $F(1,356) = 6.15$, $p = .014$, which is less than the 0.05 level of significance. The null hypothesis (H_{03}) was therefore rejected, indicating a statistically significant interaction: the urban-rural solar radiation gap was not constant across seasons but widened significantly during the dry (harmattan) season, when urban aerosol and dust loading, compounded by Saharan dust transport, is typically most pronounced, relative to the wet season, when rainfall-related atmospheric cleansing appears to have narrowed the urban-rural differential.

5. Discussion of Findings

The finding that rural areas of Nasarawa State receive significantly higher global solar radiation than urban areas is consistent with atmospheric radiative attenuation theory, which predicts that the higher aerosol and particulate loading typically associated with urban vehicular traffic, generator use, and combustion-related activity should measurably attenuate incoming shortwave solar radiation relative to less polluted rural environments (Iqbal, 1983; Falayi & Rabi, 2005). This finding is also consistent with the broader pattern of urban aerosol-related radiation attenuation documented in the international urban climatology literature, and extends this evidence to the specific, previously unstudied context of Nasarawa State.

The corroborating finding of significantly longer rural sunshine duration further strengthens confidence in the global solar radiation result, given the well-established positive relationship between sunshine duration and global solar radiation formalised in the Angstrom-Prescott model (Angstrom, 1924; Prescott, 1940; Augustine & Nnabuchi, 2009); shorter urban sunshine duration is consistent with more frequent urban atmospheric haze or particulate obscuration of direct sunlight, even in the substantial absence of cloud cover, relative to comparatively clearer rural skies.

The significant location-by-season interaction effect, with the urban-rural gap widening during the dry, harmattan-affected season, offers an important refinement to the overall urban-rural comparison: rather than a constant urban solar radiation deficit, the data suggest that urban areas are particularly disadvantaged during the dry season, when locally generated urban aerosol emissions are compounded by regional Saharan dust transport, a pattern broadly consistent with the seasonal aerosol loading dynamics documented in the wider West African atmospheric science literature. This has a direct practical implication for solar PV system design in Nasarawa State's urban areas, where system sizing calculations should account for a more pronounced dry-season radiation shortfall than a simple annual average urban-rural comparison would suggest.

These findings carry direct relevance for the Urban Heat Island theoretical strand introduced in Section 2.2.3: while this study did not statistically test the temperature-PV-efficiency pathway in detail, the elevated urban ambient temperatures generally documented in Nigerian urban climatology (Oke, 1982, as broadly applied) suggest that urban solar PV systems in Nasarawa State's urban centres may face a compounding disadvantage, receiving both lower incoming radiation and experiencing higher module operating temperatures, relative to rural systems, both factors working in the same, radiation-and-efficiency-reducing direction for urban solar PV performance.

From a rural electrification policy standpoint, these findings offer encouraging empirical support for prioritising rural areas of Nasarawa State for decentralised, off-grid solar electrification, given both the demonstrated resource advantage and the generally lower rural grid electricity access that makes off-grid solar particularly valuable in these areas (Bugaje, 1999; Sambo, 2009). For urban areas, the findings suggest that, while still technically viable for solar deployment given the still-substantial urban radiation levels observed (5.41 kWh/m²/day, comfortably within Nigeria's generally cited viable range), urban solar PV system planning should incorporate somewhat more conservative resource assumptions, particularly for dry-season performance forecasting, and that urban air-quality management interventions could plausibly yield a secondary co-benefit of enhanced urban solar resource availability over time.

6. Conclusion

This study empirically compared the solar energy potential of urban and rural areas of Nasarawa State using systematic in-situ measurement of global solar radiation, sunshine duration, and

temperature over a twelve-month period, at three urban and three rural stations, complemented by an illustrative national cross-validation exercise spanning polytechnics in all six of Nigeria's geopolitical zones. The findings revealed that rural areas of Nasarawa State receive significantly higher global solar radiation and record significantly longer sunshine duration than urban areas, and that this urban-rural solar radiation gap widens significantly during the dry, harmattan-affected season. These findings are consistent with, and extend to the specific context of Nasarawa State, established atmospheric radiative attenuation theory and the broader Nigerian and international empirical literature on aerosol-related solar radiation attenuation in urbanised environments. The study concludes that measurable, statistically significant, and seasonally variable differences in solar energy potential exist between urban and rural areas of Nasarawa State, with clear implications for evidence-based solar energy deployment planning within the State.

7. Recommendations

Based on the findings of this study, the following recommendations are made:

1. The Nasarawa State Ministry of Power and Energy and the Rural Electrification Agency should prioritise rural local government areas, such as Awe, Obi, and Wamba, for decentralised, off-grid solar electrification projects, given their demonstrated superior solar resource and generally lower existing grid electricity access.
2. Solar PV system designers and investors planning deployments in Nasarawa State's urban centres should incorporate conservative, season-specific resource assumptions, particularly accounting for the significantly wider urban-rural radiation gap observed during the dry, harmattan-affected season.
3. Urban environmental and air-quality management authorities should investigate the contribution of vehicular emissions, generator use, and construction dust to urban atmospheric aerosol loading in Nasarawa State's urban centres, given this study's evidence of a measurable associated solar radiation attenuation effect.
4. The Nigerian Meteorological Agency and Nasarawa State research institutions should expand the network of ground-based solar radiation and sunshine duration monitoring stations within the State, so as to support more geographically granular solar resource assessment beyond the six stations examined in this study.
5. Federal and State research funding agencies should support further empirical solar resource assessment studies in other Nigerian states, using the urban-rural comparative methodology demonstrated in this study, to build a more geographically comprehensive national solar resource evidence base.
6. Future researchers should extend this study by directly measuring photovoltaic module operating temperature and system-level energy yield at matched urban and rural installations, to empirically quantify the combined radiation-and-temperature effect on urban-rural solar PV performance suggested, but not directly tested, by this study's findings.

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